Appendix D Resource Variability Parameters

There are three basic resource variability parameters for renewables with variable resources (i.e. wind and solar) that are calculated for each period in ReEDS before the linear program optimization is conducted for that period. These include capacity value, operating reserve, and surplus. For each, a marginal value is calculated, which applies to new installations in the period, and an "old" value is calculated, which applies to all the capacity built in previous periods. This section describes the statistical assumptions and methods used to calculate these values.

These variable-resource parameters are calculated for a source from which the variable-resource renewable energy (VRRE) is generated and a sink to which the energy is supplied. The source is always a supply region. The user must specify the regional level for the sink. It can be a balancing authority (BA), a regional transmission organization (RTO), a NERC region, or an entire interconnect. The "old" values for these variable-resource parameters are calculated for each sink but not for each source since the old value is a single value for all the variable resource supplied to the sink.

D.1 Data inputs for the calculation of resource variability parameters

The inputs required for calculating the resource variability parameters describe the probability distributions associated with loads, conventional generator availability, and VRRE generation. For each, an expected value and standard deviation are calculated.

For loads the expected value, μ_L, is the same as the values used in the "LOAD_PCA" constraint. The standard deviation of the load, σ_L, is found from the load-duration curve of the sink region.

For conventional generator availability, the expected value is the nameplate capacity times 1 minus the forced outage rate.

$$\mu_C = \sum_q CONVCAP_{q,r} \cdot (1 - fo_q)$$

Variance of conventional generator availability is calculated thus:

$$\sigma_C^2 = \sum_q numplants_{q,r} \cdot plantsize_q^2 \cdot fo_q \cdot (1 - fo_q)$$

where

$plantsize_q$ is the input typical size of a generator of type q
$numplants_{q,reg} = CONVCAP_{q,r} / plantsize_q$

The probability distribution associated with conventional generator availability is complicated by the fact that there are can be many conventional generators and each one's availability is a binomial random variable with probability $(1 - fo_q)$ of being one. We largely avoid this complication by first combining the random variables for conventional generator availability, C, with loads, L, in the form of a random variable X where:

$$X = C - L$$

The expected value of X, μ_X, is the sum of the expected values of the other two random variables

$$\mu_X = \mu_C - \mu_L$$

and, since C and L are statistically independent:

$$\sigma_X^2 = \sigma_C^2 + \sigma_L^2$$
$$\sigma_X = \sqrt{\sigma_C^2 + \sigma_L^2}$$

where σ denotes standard deviation and σ^2 is the variance.

Future improvements in the performance of wind and solar technologies are captured in ReEDS through increased capacity factors. These improved capacity factors translate directly into improvements in the mean of a VRRE plant's generation output. ReEDS also estimates a new standard deviation for a VRRE plant based on regressions that estimate the new standard deviation as a function of the old standard deviation and the new capacity factor.

In the variable-resource parameters described below the input distributions must represent the generation from all VRRE plants contributing to a sink region, not simply a single plant. The mean value μ_R is easily calculated as the sum of the mean values of the output of the individual contributing VRRE plants. The standard deviation is complicated by the fact that the outputs of the VRRE plants are correlated with one another. For each ReEDS time slice, we have used the WSIS data to develop a correlation matrix (P_{kl}) of the Pearson correlation between each possible pair k,l of region, class, and VRRE, e.g. a correlation coefficient represents the power output between class 5 wind in region 3 and class 2 PV generation in region 14. This P_{kl} matrix is an input to ReEDS. (Currently, correlation coefficients have only been calculated for wind to wind correlations, however, we are in the process of calculating wind-load, csp-csp, wind-csp, and csp-load correlations.) The variance of the VRRE arriving at a sink region r ($\sigma_{R_r}^2$) is then calculated from this correlation matrix P_{kl} through the standard statistical formula:

$$\sigma_{R_r}^2 = \sum_{k \in R_r} \sum_{l \in R_r} P_{kl} \cdot \sigma_k \cdot \sigma_l$$

where

R_r is the set of VRRE's contributing to region r

Armed with the mean and standard deviation of all VRRE contributing to a region r, we can now calculate the variable-resource parameters - capacity value, operating reserve, and surplus. In the current version of ReEDS, we assume all combined random variables to be normally distributed, though the distribution for each individual random variable (e.g. C, L, R_r) need not be normally distributed. For example, X is assumed to follow a normal distribution defined by it's mean, μ_X, and standard deviation, σ_X. The normal distribution approximation improves in accord wtih the central limit theorem. We also have the capability of using other probability distributions, e.g. Beta function.

D.2 Capacity Value

This is the capacity credit given to the VRRE contribution to meeting the reserve margin constraint in each sink region. It is a function of the amount and type of VRREs consumed in the sink region, the dispersion of the VRRE plants contributing the energy, the electric load in the sink region, the variability of the load and the amount and reliability of conventional capacity contributing to the load in the sink region. Generally, as more VRREs are used by the sink region, their capacity value decreases. And as more renewable energy from a particular source is used, the marginal capacity value from that source decreases.

$\mathbf{CVold_r}$: For the total VRRE generation that is to be consumed in sink region r, the capacity credit, $CVold_r$, is the amount of load that can be added in every hour without changing the system reliability in sink region r, i.e. without changing the loss-of-load probability. This added load is the effective load-carrying capability (ELCC) associated with the VRRE contributed to the sink region.

To estimate $CVold_r$, we first equate the loss of load probabilities of the random variables:

$$\begin{aligned} U &= C + R_r - L \\ V &= C - (L - \Delta_L), \end{aligned}$$

where C, R_r, and L are as defined above and Δ_L is the ELCC for the VRRE in the system. Assuming C, R_r, and L are statistically independent, the variances of U and V are given by:

$$\begin{aligned} \sigma_U^2 &= \sigma_C^2 + \sigma_{R_r}^2 + \sigma_L^2 \\ \sigma_V^2 &= \sigma_C^2 + \sigma_{L-\Delta_L}^2. \end{aligned}$$

The loss of load probability with VRRE in the system is the probability that U is less than zero or $P(U < 0)$. Define $U' = (U - \mu_U)/\sigma_U$ as a standard normal variable. The probability that U is less than zero is the probability that U' is less than $-\mu_U/\sigma_U$ or $N(-\mu_U/\sigma_U)$, where N is the cumulative standard normal distirbution function. Similarly, $P(V < 0) = N(-\mu_V/\sigma_V)$ and the ELCC or Δ_L can be estimated by equating $P(U < 0) = P(V < 0)$. With these definitions, $CVold_r$ is simply Δ_L/TR_r where TR_r is the total installed VRRE nameplate capacity devoted to region r. The following shows the derivation for an expression for $CVold_r$.

$$\begin{aligned} P(V < 0) &= P(U < 0) \\ N(-\mu_V/\sigma_V) &= N(-\mu_U/\sigma_U) \\ \mu_V/\sigma_V &= \mu_U/\sigma_U \\ (\mu_C - \mu_L + \mu_{\Delta_L})/\sigma_V &= \mu_U/\sigma_U \\ \mu_{\Delta_L} &= \mu_L - \mu_C + \mu_U \cdot \sigma_V/\sigma_U \\ \Delta_L &= \mu_L - \mu_C + \mu_U \cdot \sigma_V/\sigma_U, \end{aligned}$$

where in the last equation we set $\Delta_L = \mu_{\Delta_L}$. Since μ_V is a function of $\sigma_{L-\Delta_L}^2$, which in turn depends on Δ_L itself, the above equation would be non-trivial to solve and would likely increase the run-time significantly. Instead of solving exactly, we estimate $\sigma_{L-\Delta_L}^2$ based on the ELCC or Δ_L of previous periods and use the result to find:

$$CVold_r = CF_r - \mu_U \cdot (1 - \sigma_V/\sigma_U)/TR_r,$$

where CF_r is the average capacity factor of the VRRE in the system and is defined by $CF_r = \mu_{R_r}/TR_r$.

$\mathbf{CVmar_{c,i,r}}$ is the marginal capacity value associated with the addition of class c VRRE capacity in a source region i delivered to a sink region r. The calculation for $CVmar_{c,i,r}$ is very similar to the one for $CVold_r$. $CVmar_{c,i,r}$ is calculated using the random variable U above and the random variable

$$W = C + (R_r + \delta_{R_r,c,i}) - (L + \delta_L),$$

where $\delta_{R_r,c,i}$ is an incremental amount of class c VRRE from region i that can serve region r, and δ_L is the effective load carrying capacity for this increment of VRRE. δ_L is calculated similarly to the calculation for Δ_L above:

$$
\begin{aligned}
P(W < 0) &= P(U < 0) \\
N(-\mu_W/\sigma_W) &= N(-\mu_U/\sigma_U) \\
\mu_W/\sigma_W &= \mu_U/\sigma_U \\
(\mu_C + \mu_{R_r} + \mu_{\delta_{R_r,c,i}} - \mu_L + \mu_{\delta_L})/\sigma_W &= \mu_U/\sigma_U \\
\mu_{\delta_L} &= \mu_C + \mu_{R_r} + \mu_{\delta_{R_r,c,i}} - \mu_L - \mu_U \cdot \sigma_W/\sigma_U.
\end{aligned}
$$

Finally, $CVmar_{c,i,r}$ is equal to $\delta_L/\delta_{R_r,c,i}$ or equivalently,

$$CVmar_{c,i,r} = CF_{c,i} - (\frac{\sigma_W}{\sigma_U} - 1) \cdot \mu_U/\delta_{R_r,c,i}.$$

D.3 Operating Reserve Requirement

Operating reserve includes spinning reserve, quick-start capability, and interruptible load that can be dispatched to meet unanticipated changes in loads and/or power availability. There is no standard approach for estimating the level of operating reserve required. Some NERC regions assume that operating reserve must be at least as large as the largest single system contingency, e.g. the failure of a nuclear power plant. Others have reasoned that a system should have enough operating reserve to meet 7% of peak load (reduced if hydro is available). We assume in ReEDS that the normal operating reserve ($NOR_{r,m}$) required by a sink region r is proportional to the load ($L_{r,m}$) and conventional generation ($G_{r,m}$) in the region.

VRREs can induce a need for additional operating reserve beyond the usual requirement. ReEDS calculates the total operating reserves induced by all load, conventional generation, and VRREs in the system ($TOR_{r,m}$) and the operating reserves induced at the margin ($ORmar_{r,m}$) by the addition of an increment of VRRE capacity.

$\mathbf{TOR_{r,m}}$ is the total operating reserve required in region r due to load, conventional generation, and all existing VRRE capacity contributing to sink region r (R_r). By assuming that the normal operating reserve is a 2-sigma reserve, we can estimate the sigma, $\sigma_{NOR_{r,m}}$, associated with the normal system operation (operating reserve required for load and conventional generation) as:

$$
\begin{aligned}
NOR_{r,m} &= \frac{0.03 \cdot (L_{r,m} + G_{r,m})}{2 \cdot L_{r,m}} \\
\sigma_{NOR_{r,m}} &= NOR_{r,m} \cdot (L_{r,m} - R_r)
\end{aligned}
$$

Since the normal system issues that require the normal operating reserve occur independently of the resource variability of VRREs, the variances of the two can be added to give the variance of the total. The total operating reserve is then assumed to be twice the standard deviation of the total.

$$TOR_{r,m} = 2 \cdot \sqrt{\sigma^2_{NOR_{r,m}} + \sigma^2_{R_r}}$$

where

σ_{R_r} is assumed to be the standard variation of the output of all existing VRREs contributing to sink region r.

ORmar$_{\mathbf{c,i,r}}$ is the marginal operating reserve requirement induced by the next MW of class c VRRE installed in region i that contributes generation to sink region r. It is calculated as the difference in the operating reserve required with an increment $\Delta R_{c,i,r}$ of additional VRRE capacity, minus that required with only the existing VRRE with the difference divided by the incremental VRRE capacity $\Delta R_{c,i,r}$.

$$ORmar_{c,i,r,m} = \frac{2}{\Delta R_{c,i,r}} \cdot \left(\sqrt{\sigma^2_{NOR_{r,m}} + \sigma^2_{R_r + \Delta R_{c,i,r}}} - \sqrt{\sigma^2_{NOR_{r,m}} + \sigma^2_{R_r}} \right)$$

D.4 Surplus

At high levels of VRRE penetration, there are times when the VRRE generation exceeds that which can be used in the system. This "surplus" VRRE generation must then be curtailed. ReEDS calculates the fraction of VRRE generation from existing VRRE plants ($Surplusold_r$) that is surplus as well as the fraction of generation from new VRRE plants ($Surplusmar_r$) that is surplus. ReEDS uses these surplus values to reduce the useful energy contributed by VRREs, making them less cost-effective generators.

SurplusOld$_{\mathbf{r}}$ is the expected fraction of generation from all the VRREs consumed in sink region r that cannot be productively used, because the load is not large enough to absorb both the VRRE generation and the must-run generation from existing conventional sources. This situation occurs most frequently in the middle of the night when loads are small, base-load conventional plants are running at their minimum levels, and the wind is blowing.

To calculate $Surplusold_r$, we use the random variable Y defined in the capacity value discussion above as the must-run conventional base-load generation M minus the load L plus the VRRE generation R.

$$Y = M - L + R$$

Next, we define the surplus VRRE at any point in time, S, as

$$\text{If } Y < 0, S = 0$$
$$\text{If } Y > 0, S = Y$$

Then the expected surplus μ_S can be calculated from the density function of Y, g(y) as follows:

$$\mu_S = \int_{-\infty}^{\infty} sf(s)ds$$
$$\mu_S = \int_{-\infty}^{0} sf(s)ds + \int_{0}^{\infty} sf(s)ds$$
$$\mu_S = 0 + \int_{0}^{\infty} yg(y)dy$$

The density function of y can be found by convolving the density function of $M - L$ together with the density function of the VRRE. However, similar to that which was done in the calculation of the VRRE capacity value above, we approximate normal distributions for both $M - L$ and R. With the normal distribution assumption, the value of μ_S can be quickly found in ReEDS with the analytical formula derived below:

Now if we assume, as we did in the $CVmar$ and $ORmar$ calculations above, that by the central limit theorem, Y can be well approximated by a normal distribution, and we define the standard normal variable Y' as $Y' = (Y - \mu_Y)/\sigma_Y$, then

$$Y = Y' \cdot \sigma_Y + \mu_Y, \text{ and}$$
$$dY = \sigma_Y dY'$$

Thus

$$\mu_S = \int_0^{\infty} y g(y) dy$$
$$\mu_S = \int_{-\mu_Y/\sigma_Y}^{\infty} (y'\sigma_Y + \mu_Y) \cdot g(y'\sigma_Y + \mu_Y) \cdot \sigma_Y dy'$$
$$\mu_S = \int_{-\mu_Y/\sigma_Y}^{\infty} \sigma_Y^2 \cdot y' \cdot g(y'\sigma_Y + \mu_Y) dy' + \int_{-\mu_Y/\sigma_Y}^{\infty} \mu_Y \cdot \sigma_Y \cdot g(y'\sigma_Y + \mu_Y) dy'$$

Assuming Y is normally distributed, as stated above:

$$\mu_S = \int_{-\mu_Y/\sigma_Y}^{\infty} \sigma_Y^2 \cdot y' \left(\frac{1}{\sigma_Y \sqrt{2\pi}}\right) \exp\left(\frac{(-y'\sigma_Y + \mu_Y - \mu_y)^2}{2\sigma_Y^2}\right) dy'$$
$$+ \int_{-\mu_Y/\sigma_Y}^{\infty} \mu_Y \cdot \sigma_Y \left(\frac{1}{\sigma_Y \sqrt{2\pi}}\right) \exp\left(\frac{(-y'\sigma_Y + \mu_Y - \mu_y)^2}{2\sigma_Y^2}\right) dy'$$
$$\mu_S = \int_{-\mu_Y/\sigma_Y}^{\infty} \frac{\sigma_Y \cdot y'}{\sqrt{2\pi}} \exp\left(\frac{-y'^2}{2}\right) dy' + \int_{-\mu_Y/\sigma_Y}^{\infty} \frac{\mu_Y}{\sqrt{2\pi}} \exp\left(\frac{-y'^2}{2}\right) dy'$$
$$\mu_S = \frac{\sigma_Y}{\sqrt{2\pi}} \exp\left(\frac{-\mu_Y^2}{2\sigma_Y^2}\right) + \mu_Y\Big(1 - N_{0,1}(-\mu_Y/\sigma_Y)\Big)$$

Where $N_{0,1}$ is the standard normal distribution with mean 0 and standard deviation 1.

Then $Surplusold_r$ is the difference between the expected surplus with VRRE, μ_S and the expected surplus were there no VRRE generation consumed in sink region r, μ_{SN}, divided by the total VRRE capacity contributing to sink region r, R_r. Or

$$Surplusoldr = (\mu_S - \mu_{SN})/R_r$$

Normally μ_{SN} would be zero, as the conventional must-run units would not be constructed in excess of the minimum load. However, with our assumption of a normal distribution for Y, we do introduce some non-zero probability that Y could be positive even if there were no VRREs, i.e. that the generation from must-run units could exceed load. Thus, it is important to calculate μ_{SN} and to subtract it from μ_S to remove the bulk of the error introduced by the normal distribution assumption. μ_{SN} is calculated in exactly the same way as μ_S, but with no VRREs included.

Must-run conventional capacity is defined as existing available (i.e., not in a forced outage state) coal and nuclear capacity in sink region r times a minimum turn-down fraction, *MTDF*. The expected value of the must-run capacity of type q available at any given point in time, μ_{M_q}, is thus:

$$\mu_{M_q} = CONVCAPq, r * (1 - FOq) * MTDFq$$

where

$CONVCAP_{q,r}$ is the existing conventional capacity in sink region r of type q.
$MTDF_q$ is 0.45 for old (pre-2006) coal plants,
0.35 for new (post-2006) coal plants,
1.0 for nuclear plants.

SurplusMar$_{\mathbf{c,i,r}}$ is the fraction of generation from a small addition $\Delta R_{c,i,r}$ of class c VRRE installed in supply region i destined for sink region r that cannot be productively used because the load is not large enough to absorb both the VRRE generation and the must-run generation from existing conventional sources. It is calculated as:

$$Surplusmar_{c,i,r} = (\mu_{SR+\Delta R_{c,i,r}} - \mu_S)/\Delta R_{c,i,r}$$

Where $\mu_{SR+\Delta R_{c,i,r}}$ is calculated in exactly the same way as μ_S, but with $\Delta R_{c,i,r}$ MW of VRRE added in region i.